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Planar Dipole Input Resistance vs. Trace Thickness for Different Materials

by Seth A McCormick

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14. ABSTRACT

This report details a numerical study on the impact of trace thickness on the antenna's input resistance when using the conductivities of the following materials: copper trace, copper paint, silver-loaded ink, indium tin oxide (ITO), poly-ethylenedioxythiophe (PEDOT), carbon fiber composite, and carbon fiber. An antipodal planar dipole, measuring 305 mm x 4 mm and resonant at 450 MHz, is used for simulating the different materials. The antipodal planar model is constructed, measured, and compared to simulation results from commercial electromagnetic (EM) solvers to validate the structure. The results show that the antipodal structure performs as it should. The simulation results show that the ohmic resistance increases over the frequency band and decreases as trace thickness is increased. The efficiency is also improved as the trace thickness is increased.

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1. Introduction

Antennas are commonly constructed from sheets or pieces of metal due to the excellent properties that natural conductors possess, but there are times when metal may hinder the antenna's function. Cost, material waste due to manufacturing, environmental unfriendliness, weight, and inflexibility are disadvantages of conventional fabrication that can limit range of use. A radio frequency identification (RFID) antenna tag, for example, needs to be cheap and easy to manufacture, and capable of maintaining function while flexing.[1,2] These requirements result in the need for more adequate manufacturing methods such as inkjet printing.[2]

As such, good antenna construction requires careful consideration of design constraints, as well as the operational requirements, in order to achieve the desired system performance. In addition to cost and size, the material used to construct the antenna must be considered. The material itself can actually limit the application of the antenna. For example, a copper-based antenna is well suited and preferred for most applications, but for ultra-lightweight applications, copper may be too heavy, necessitating a suitable substitute, such as a carbon fiber composite. Alternative conducting materials can also give the antenna designer increased flexibility from an antenna construction standpoint. For example, conductive polymers may be used for transparent antennas and silver-loaded ink for flexible antennas.

Of course, just substituting one material for another does not necessarily mean that the antenna will function efficiently. Carbon fiber composites and conductive polymers possess conductivities several orders of magnitude lower than that of copper, requiring thicker traces to improve the efficiency. Unfortunately, continuing to thicken the trace can also be detrimental as additional material can have a detrimental effect on the input resistance and increase costs.

This report explores the performance of a planar dipole antenna constructed as an antipodal structure. The physical aspects would allow this antenna to be constructed from different materials and through different manufacturing methods, preferably inkjet printing. This report validates the planar antipodal structure (as not having a negative impact on antenna performance), the use of a tapered micro-strip feed line, and the reduced ground plane.

This report also simulates the dipole with seven different material conductivities over the frequency band and as a function of trace thickness. Copper paint and silver-loaded ink were chosen since the main purpose for this antenna design is to be constructed from a material that would allow for flexibility. Indium tin oxide (ITO) and poly-ethylenedioxythiophe (PEDOT) are materials used for clear electronics, with the possibility of being used for flexible electronics as well.[3,4] Carbon fiber and carbon fiber composite is considered due to the need of ultra-lightweight materials in many applications.[1]

2.   Baseline Model

The antenna under test is an antipodal planar dipole antenna milled from Rogers Duroid[TM] 5870. The dipole was chosen for its simplicity, as it is easily realized and fed, and for its desirable input impedance.[5] The antipodal construction allows for the use of a standard micro-strip line feed. The feed is connected to an end-launch SMA connector. The ground plane side of the dipole was trimmed in order to remove unnecessary metal, as can be seen in Fig. 1 (left).
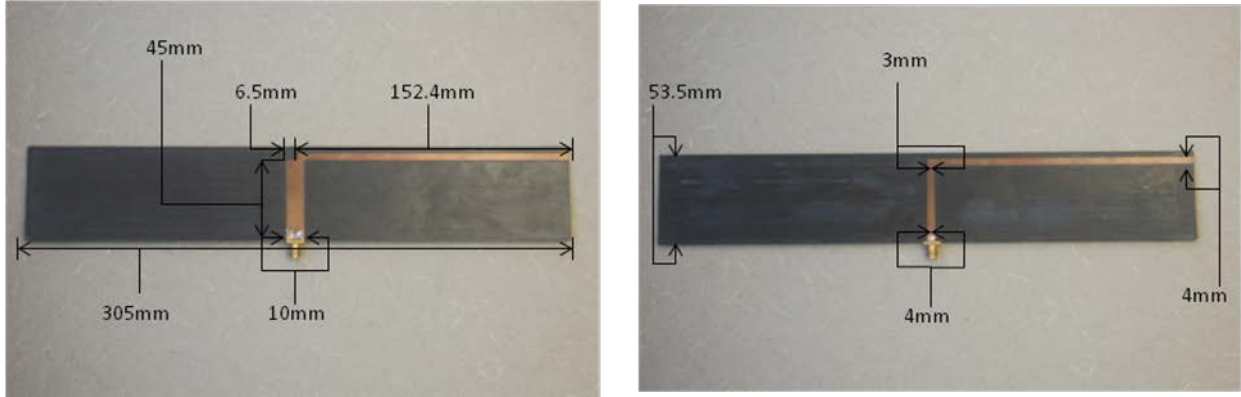

Fig. 1   Ground (GND) view (left) and top view (right)

Besides allowing for the use of an end-launch SMA connector, the micro-strip line's main advantage lies in impedance matching. The impedance of a half-wave dipole is very well known at 73 Ω.[5] Most commonly used transmission lines, however, are designed for input impedance with a real component of approximately 50 Ω. This presents a problem, as attaching the dipole directly to a 50-Ω transmission line would cause an impedance mismatch and increased reflected power. However, if the characteristic impedance of a transmission line varies gradually, then near perfect impedance matching can be achieved.[6] This method was used on the antipodal dipole by gradually tapering the micro-strip line until a proper match was achieved.

The micro-strip line gives an added bonus by eliminating the need for a balun. The dipole is a balanced antenna, which means that the current flowing in one arm is out of phase with the current flowing down the other arm.[6] A coax transmission line is not balanced and, when connected directly to the dipole, would cause the antenna to act in unpredictable ways necessitating the use of a balun.[6] The micro-strip line removes this necessity.

Using FEKO[7] and GEMS,[8] the dipole was simulated using two different methods, the method of moments (MOM) and finite-difference time-domain (FDTD), respectively. The use of two different codes was to check the validity of the simulations with different computational methods; if both codes agree with each other and with the data, then the simulation model is confirmed to be accurate. The simulation models (Fig. 2) differ slightly in that FEKO uses an

edge source whereas GEMS uses an imbedded pin source. Simulations show that the differences are negligible at best. The constructed antenna has some extra dielectric at the top compared to the simulation models, but that also has negligible impact at best. The antenna was measured in an indoor tapered anechoic chamber (located at the Adelphi Laboratory Center), using a SATIMO SH400 Dual Ridge Horn (SGA) as the transmitter. Several measurements were taken for both the gain sweep and the pattern sweep, with the three best gain sweeps averaged together for error analysis.
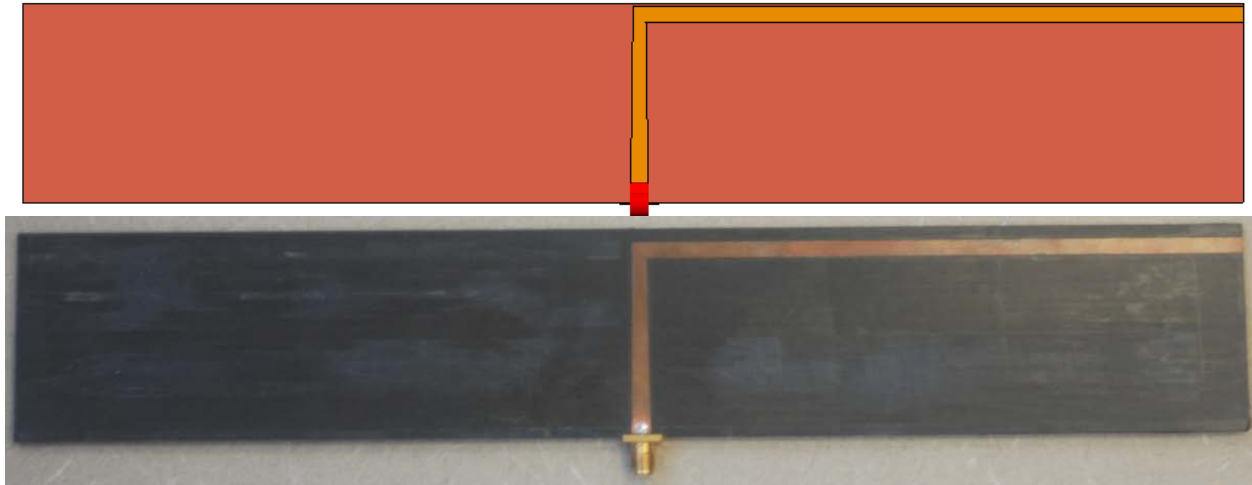

Fig. 2   Simulation model (top) and constructed model (bottom)

Comparing the reflection coefficient for the dipole (Fig. 3) simulated in GEMS and FEKO shows that there is some disagreement between the two codes as to where resonance occurs, but FEKO does show the better match. This is to be expected considering that FEKO simulated the dipole using MOM while GEMS uses FDTD, and the differences are caused by one code (MOM) being based in the frequency domain and the other (FDTD) being based in the time domain. The measured reflection coefficient shows a resonance that is about 10 MHz lower than what FEKO predicted and about 14 MHz lower than what GEMS predicted at about 427 MHz. While the measured and simulated reflection coefficient shows a resonance not at the desired 450 MHz, the difference is negligible enough, especially since all three curves show that the dipole is still well matched at 450 MHz.
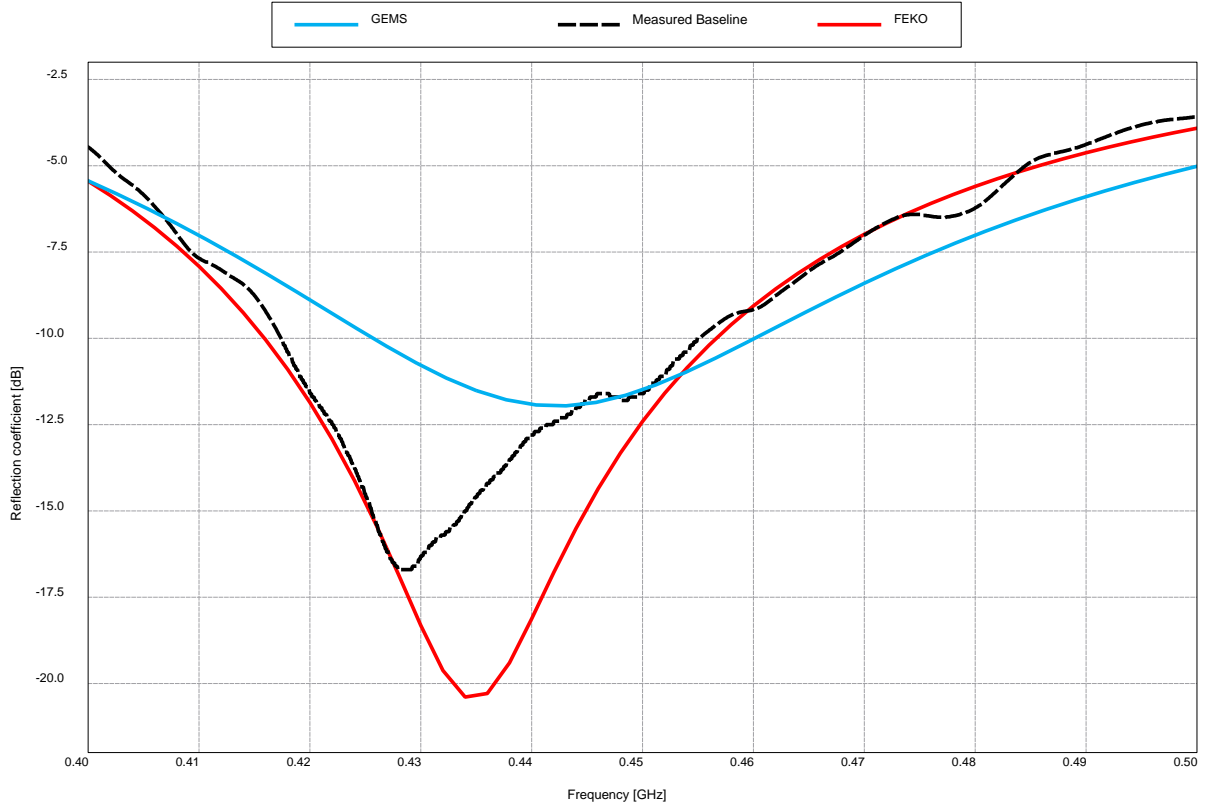
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Fig. 3 Reflection coefficient

The gain versus frequency comparison (Fig. 4) shows that there is agreement between the two codes. The measured gain, however, is high—nearly 0.4 dBi higher than what a dipole should be at 2.1 dBi. It is possible that there may be some resonance occurring within the chamber over the frequency band that could constructively interfere with the transmitted signal, resulting in an apparent increase in signal power received by the dipole. This may very well be the case, as the turntable that the dipole sits several feet above was measured to be about 0.75λ in width. The resultant error from calibration and three gain sweeps is ±0.7 dB. The majority of the error is facilitated by the fact that two of the gain sweeps were done without an absorber on the turntable, showing the detrimental impact the turntable has on measurements.
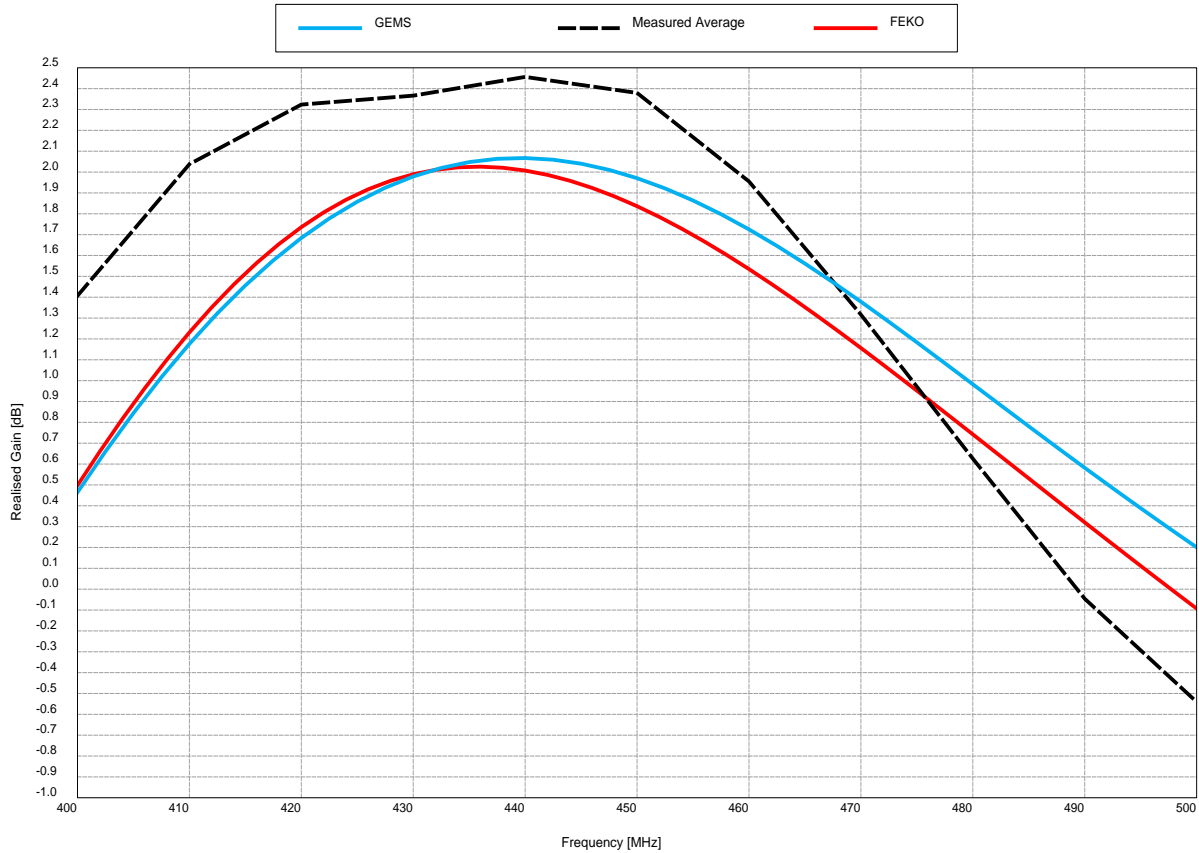
Fig. 4   Gain vs. frequency

The pattern (Fig. 5) also shows some abnormalities. Between 90° and 150°, the pattern trace shows a dip in power, which corresponds to the door side of the chamber; this may be due to some particular interference associated with that particular side of the chamber. What may be causing this interference is difficult to say. The effect of the turntable, as mentioned before, may cause some issues, such as a slightly higher gain and nulls that are not as deep, but all patterns taken show that the distortion is clearly located door side. However, regardless of the abnormality, the pattern shapes agree relatively well with one another.
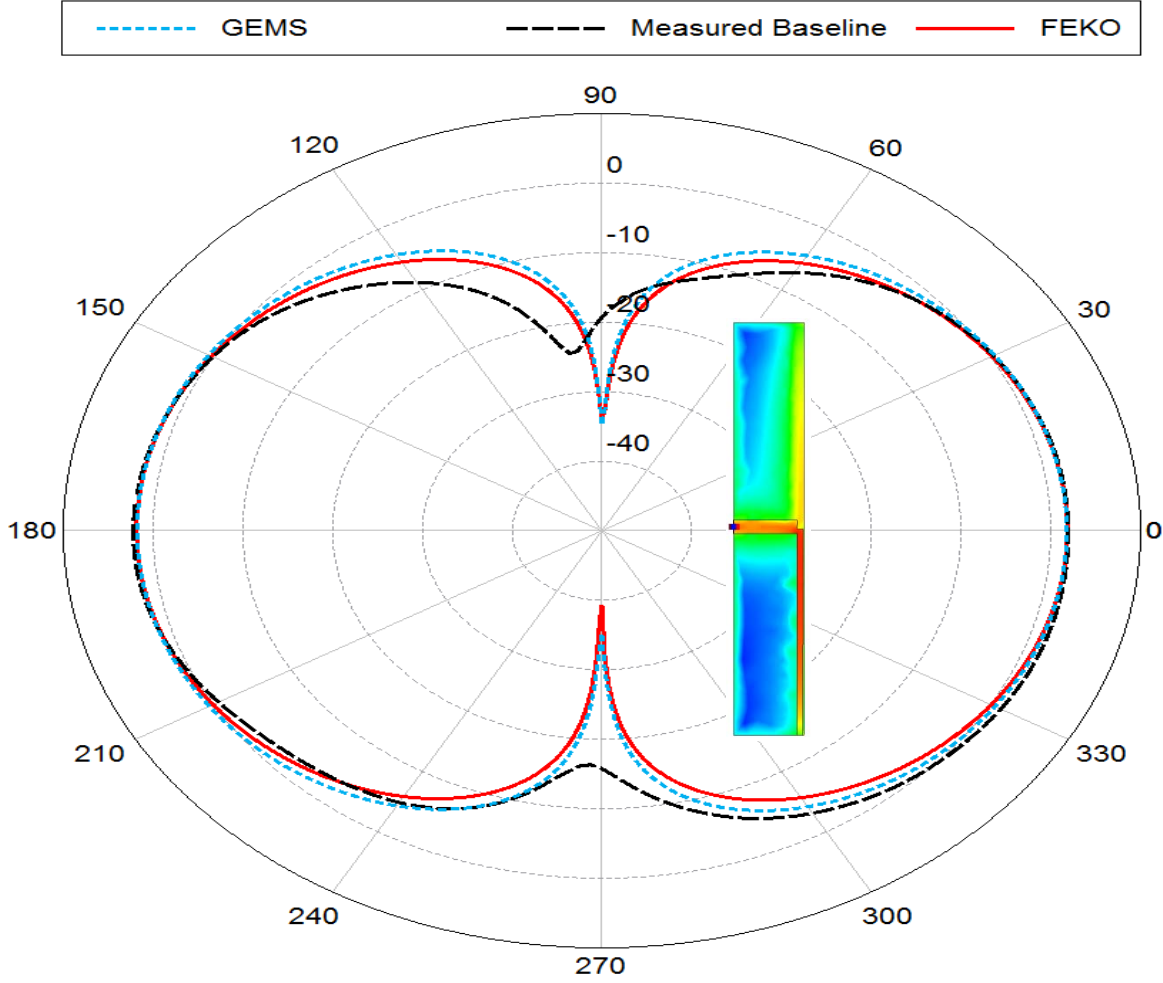
Fig. 5   Radiation pattern and current distribution at 450 MHz

It is clear that the dipole performs as it should, albeit with some issues in measurements due to chamber effects. The chosen antenna structure and the modifications made (antipodal structure, tapered strip line, and reduced ground plane) are validated as having no negative impact on the dipole's performance.

3.   Ohmic Resistance for Different Material Conductivities

This section details the ohmic resistance for the antipodal dipole structure as a function of conductivity across the frequency band of 400 to 500 MHz and as a function of trace thickness. The impact on antenna efficiency is also shown. Due to the difficulty with lossy materials in the time domain, the simulations were all done using FEKO. The goal is to present a family of curves that can be used as a reference for antenna input resistance for this dipole or any similar antenna that may be constructed from any conductive material. The dipole was simulated without

the dielectric substrate in order to decrease simulation time and extract the dipole input impedance.

The materials chosen for simulation (Table 1) by no means limit the use of the curves to only those materials, but were chosen as a general case for particular classes of materials.

Table 1   Materials and associated conductivities

Material	Conductivity (S/m)
Copper trace (baseline material)	$\sim10^7$
Methode conductive ink 9101 (silver Ink)	$\sim6.67\times10^6$
Blue Water Marine Paint® (copper paint 59.5% metallic)	$\sim5.95\times10^6$
ITO[3]	$\sim10^6$
PEDOT[3]	$\sim10^5$
Pure carbon fiber[9]	$\sim7\times10^4$
Cera Materials carbon fiber composite (carbon matrix)	$\sim3.33\times10^4$

Copper trace is the most commonly used material for planar antenna construction and is therefore the baseline. Both conductive silver ink and copper marine paint offer the advantage of flexible and easy-to-manufacture antennas; in some cases, these antennas could even be manufactured in the field though spray-on application. ITO is the most common material used for transparent conductors, such as electronic displays and transparent antennas for cars, but its brittle nature limits its applications.[3,4] PEDOT is a transparent conductive polymer that is more durable than ITO, but lacks reasonable conductivity.[3] Carbon fiber is an excellent choice for ultra-lightweight applications that also need a durable antenna, but it has a low conductivity, and because the fibers must be bonded together in a composite structure for use, the conductivity is further decreased.[1]

In order to determine the ohmic resistance for the dipole (Fig. 6), the radiation resistance across the frequency band in question needed to be found. This was done by simulating the dipole under the perfect electrical conductor (PEC) condition (Fig. 7) over the frequency band. The real impedance simulated under the PEC condition is just the radiation resistance of the dipole since there are no ohmic or dielectric losses attributed to the medium. Assuming an antenna circuit equivalent, the ohmic resistance of the dipole can be found by subtracting the PEC resistance from the simulated resistance for any of the materials.
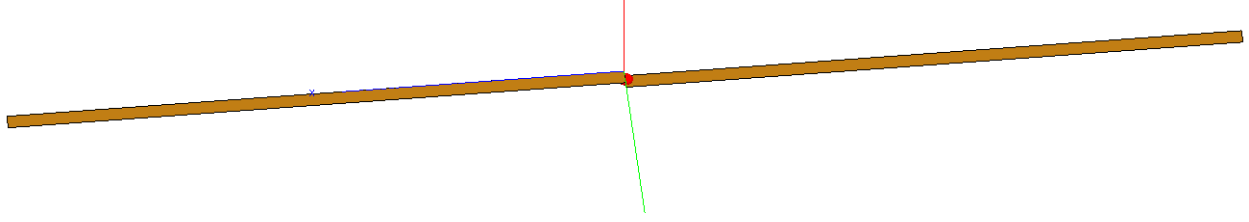
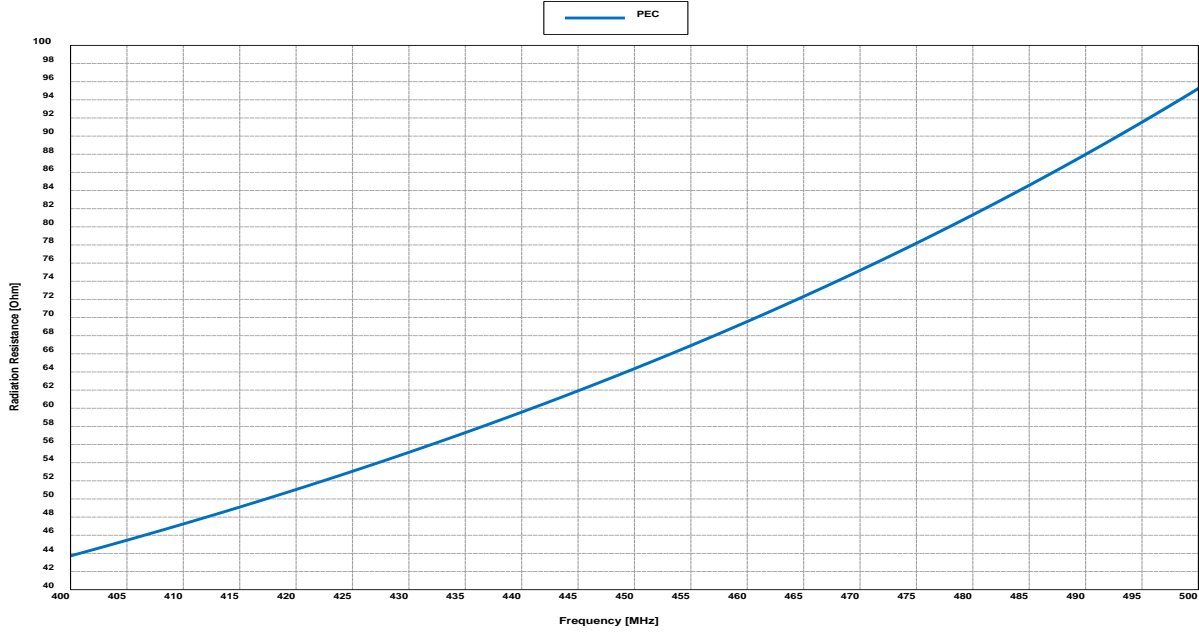Fig. 6　Material conductivity simulation model

Fig. 7　Dipole resistance under PEC condition

Figure 8 shows the input resistance for the dipole simulated between 400 and 500 MHz with a trace thickness of 20 microns. It is clear that the baseline material, silver ink, and copper paint all perform relatively the same with negligible difference (Fig. 9). ITO also performs very well, with only an increase of about 1 Ω. Both PEDOT and fiber show near a 2 orders of magnitude increase in resistance over copper, while the carbon fiber composite is at least 100 times worse than pure copper. The efficiency (Fig. 10) shows that the antenna would perform well for ITO, copper, silver ink, and copper paint, but losses in efficiency near 25% for PEDOT, 35% for fiber, and at least 55% efficiency loss for the fiber composite suggest a significant decrease in antenna performance when using materials with conductivities below 10^6 s/m.
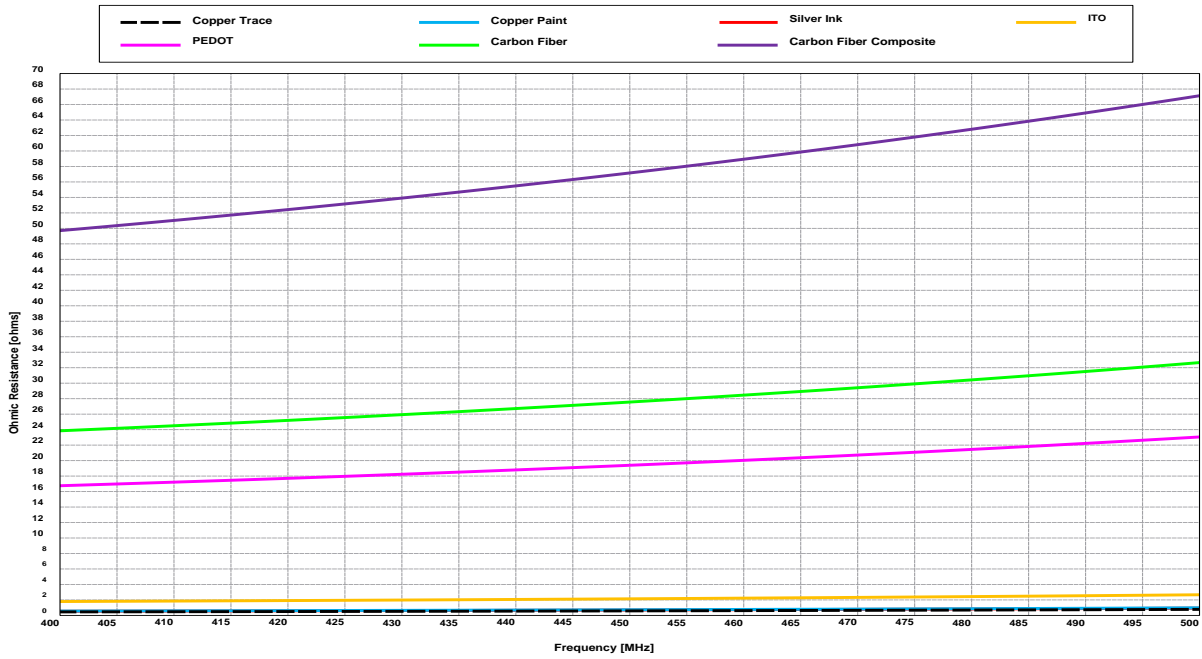
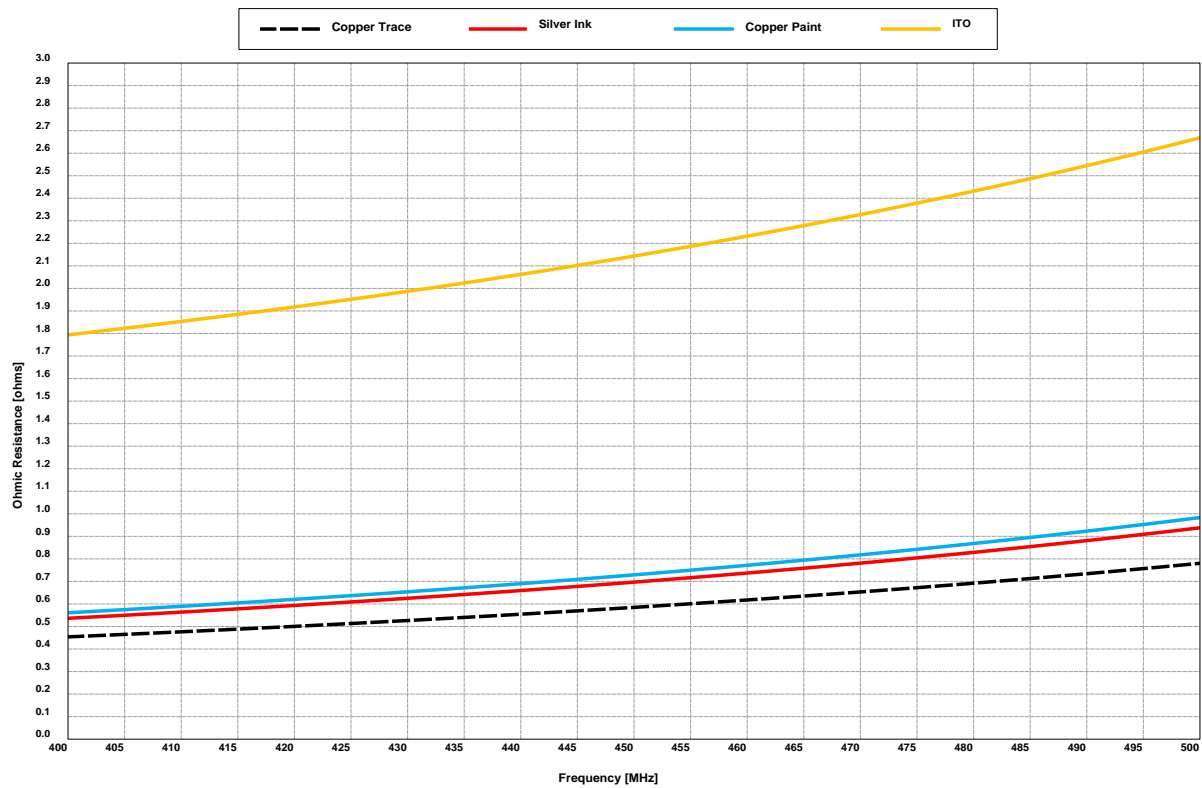Fig. 8   Ohmic resistance at 20 microns

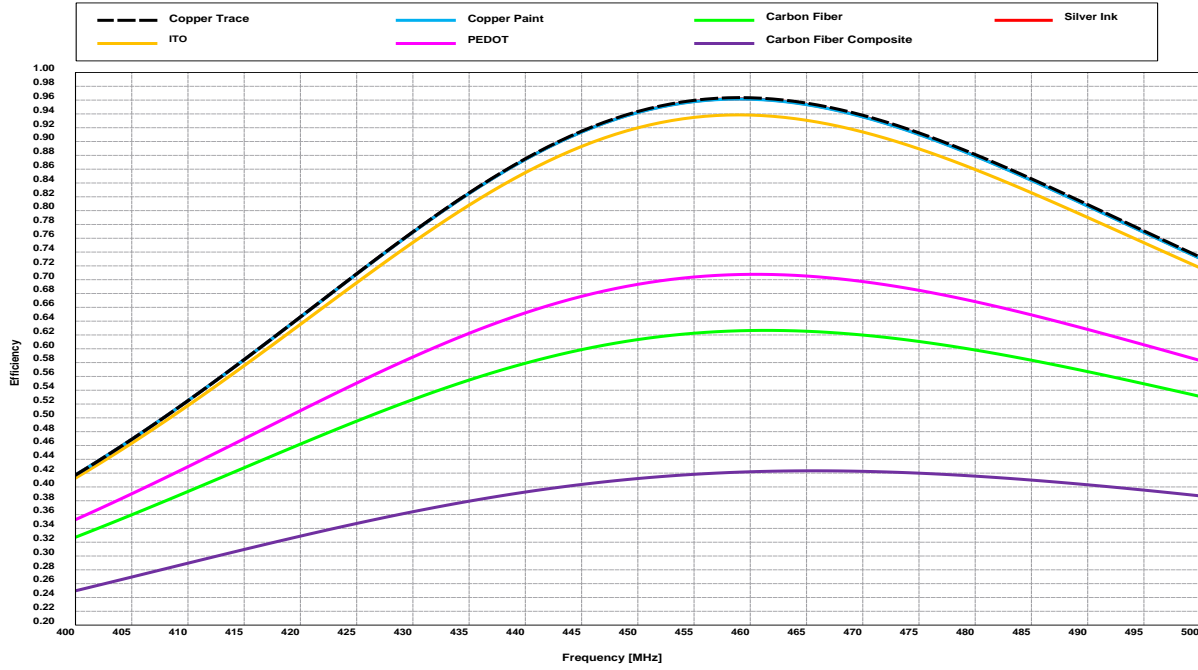Fig. 9   Baseline, silver ink, copper paint, and ITO

Fig. 10   Dipole efficiency at trace thickness 20 microns

With the trace thickness doubled to 40 microns, the dipole's ohmic resistance (Fig. 11) reduces by as much as half from that seen at 20 microns. This is to be expected, as resistance is inversely proportional to the product of conductivity and material thickness ($1/\sigma t$); if the trace thickness doubles, then the resistance halves. Taking a look at ITO, copper, silver ink, and copper paint (Fig. 12)**,** the improvement achieved by doubling the thickness is nearly negligible; this is to be expected, as skin effect dictates that after a thickness of a few skin depths, any additional material produces negligible resistance improvements.
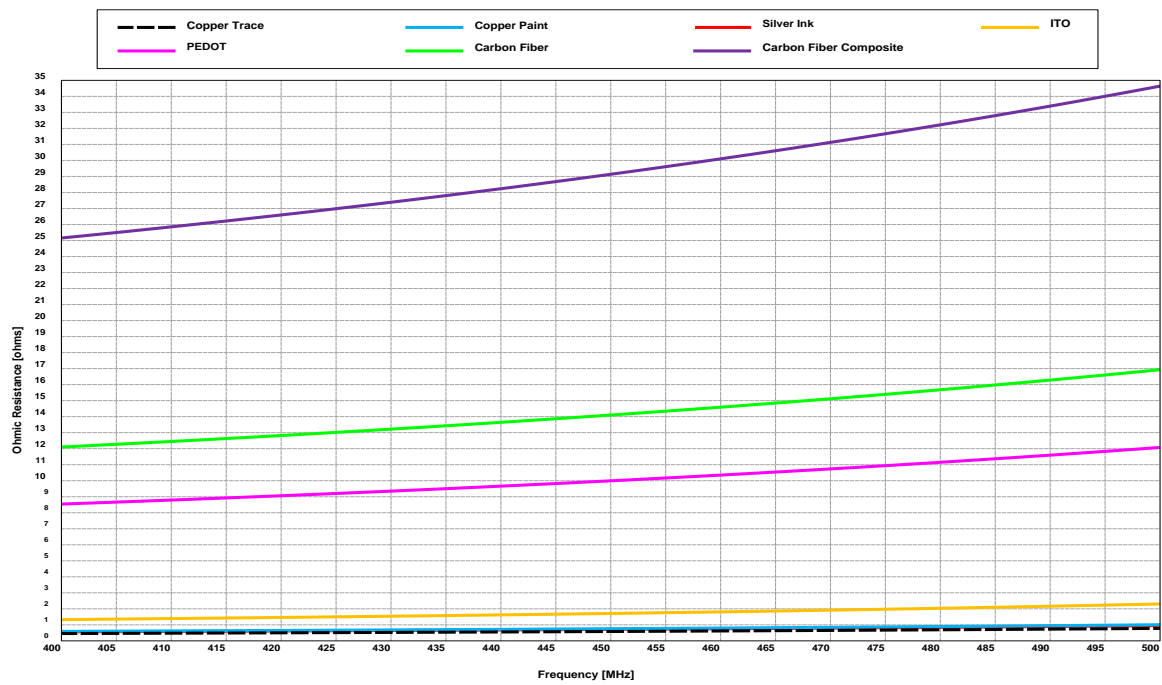
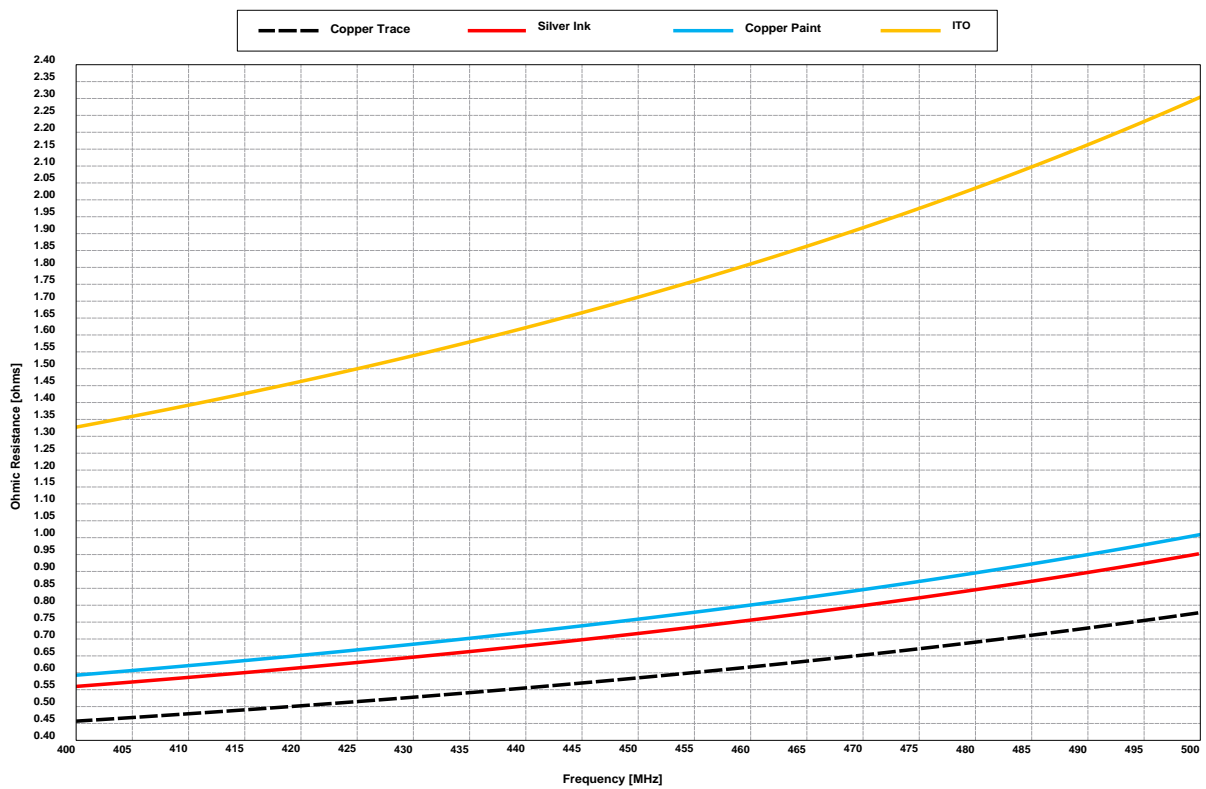Fig. 11   Ohmic resistance at 40 microns

Fig. 12   Baseline, silver ink, copper paint, and ITO

At 40 microns, the efficiency improves substantially as the carbon fiber composite sees an increase in efficiency by about 20% and the fiber alone improves by about 16%. PEDOT sees a more modest gain in efficiency at 10%, while the other four materials see less than a 1% improvement in efficiency (Fig. 13).
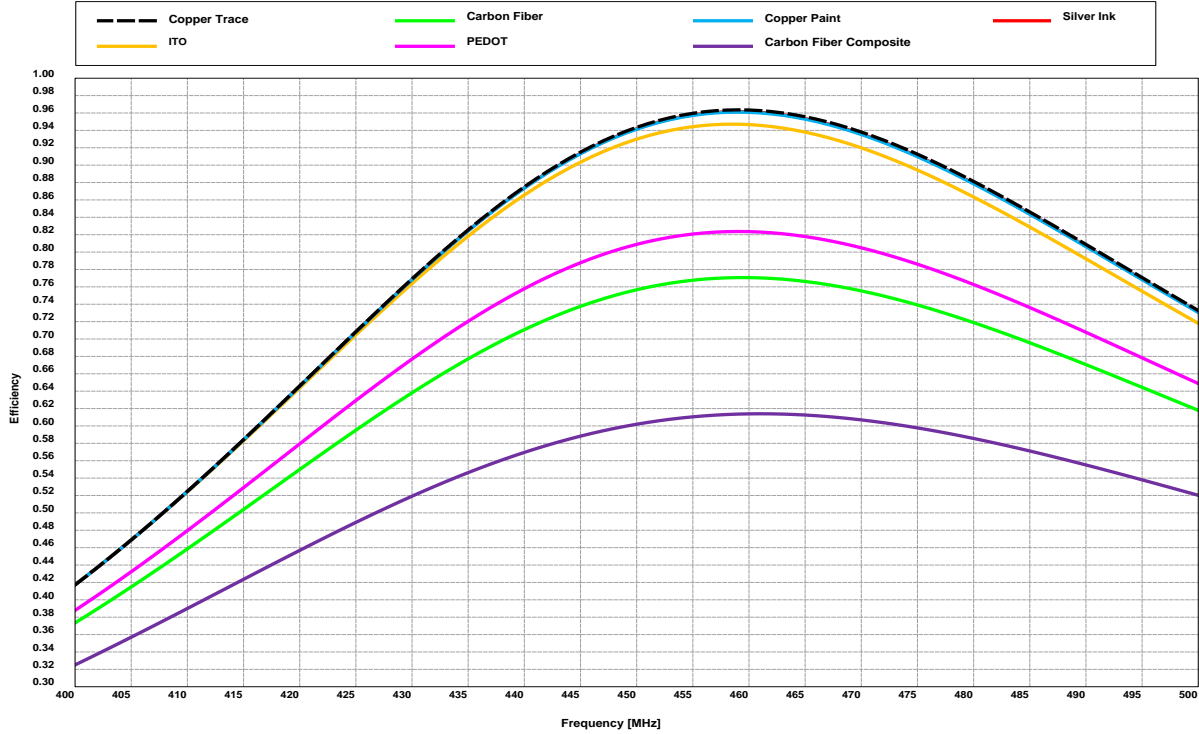

Fig. 13   Dipole efficiency at trace thickness of 40 microns

Figure 14 shows the ohmic resistance varying as a function of trace thickness from 0.5 to 20 microns at 459 MHz. The plot shows a drastic increase in resistance as the trace thickness is decreased. PEDOT, carbon fiber, and carbon fiber composite have erroneously high resistances when the trace thickness is less than 12 microns, a significant problem that highlights the issues with using materials with low conductivities. ITO fairs quite a bit better than the less conductive materials, being as much as 7 times better than the worst case. Copper, silver ink, and copper paint (Fig. 15) show some improvement to start out, but quickly reach a negligible value at a trace thickness of approximately 2 microns.

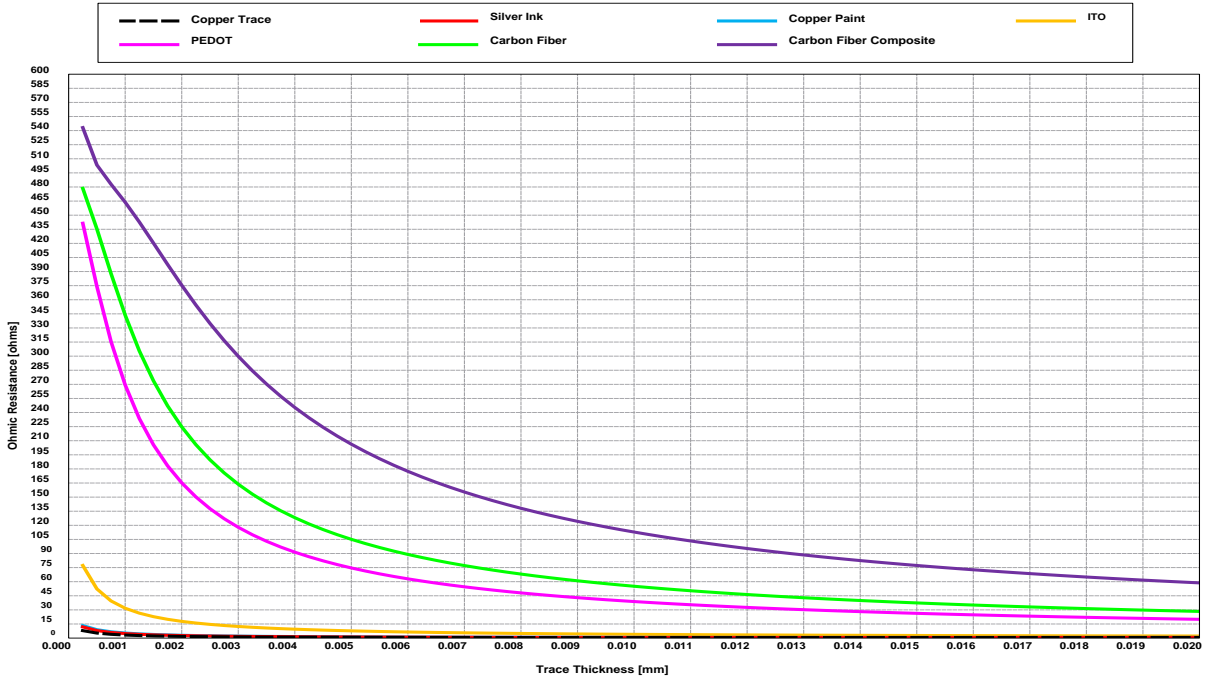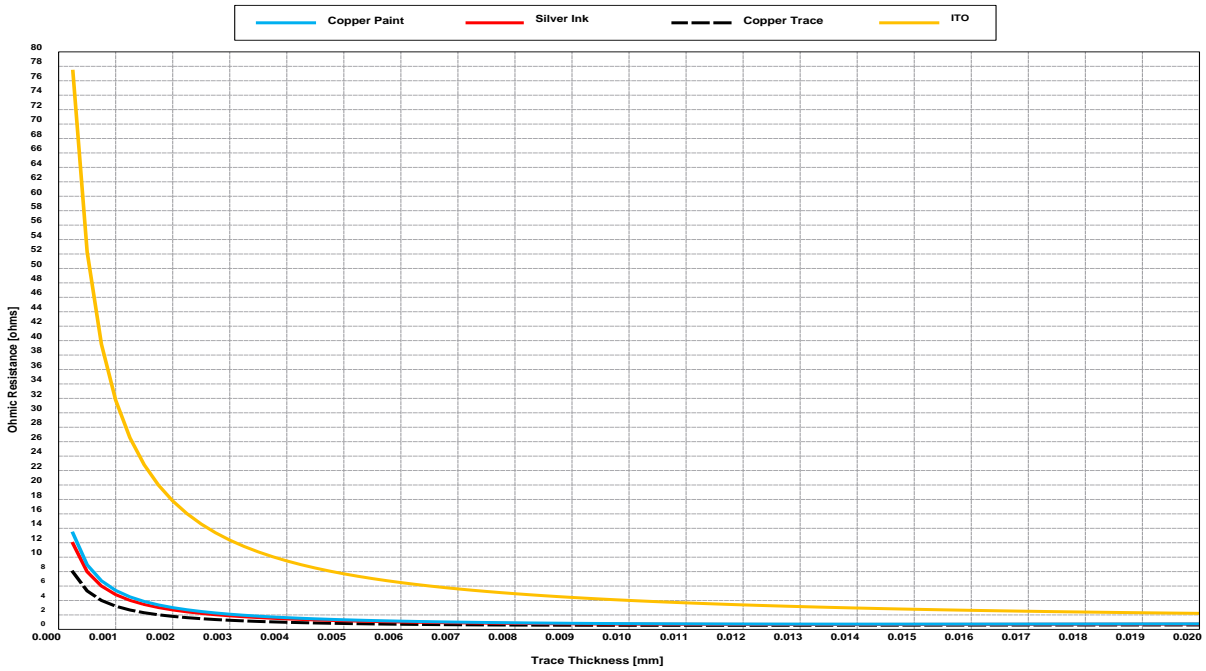Fig. 14   Ohmic resistance vs. trace thickness

Fig. 15   Baseline, silver ink, copper paint, and ITO

It is important to note that these plots do not take into account the particular material properties that can affect their actual performance. For the materials dominated by metal (i.e., paint and trace), the curves shown will accurately portray the results of an antenna constructed from those

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materials. Silver-loaded ink is affected by more than just its measured conductivity. When printing, for example, curing temperatures and resolution play an important role in maintaining a uniform trace. The silver particles in the ink must also overlay as to create paths for current to flow.[2,10,11]

The use of transparent conductive polymers renders them subject to their thickness for transparency and not just for good input resistance. The thicker a conductive polymer trace is, the more conductive it is, but for the more commonly used polymers (i.e., ITO), the maximum allowed thickness for adequate transparency is much less than a half micron.[4] Structural concerns for the printed trace also exist as such a thin trace would result in an antenna that is too brittle for use, necessitating design features such as a mesh antenna structure.[4] Future research into alternative materials (i.e., PEDOT) and material doping to improve electron mobility (a parameter that both transparency and conductivity are dominated by) would help to alleviate problems.[3,4].

Carbon fibers require a composite scheme in order to be implemented as a structure. How the fibers are weaved and what resin is used to bind them has a dominate impact on the impedance of the structure.[1] Resins are not typically very conductive, increasing the resistance of the structure. The fibers themselves are more conductive along their lengths and not their radii; this requires a well-thought-out structure to take advantage of their conductive nature. Most commonly used carbon fiber composites have a woven fiber structure to help maximize the surface conductance.[1] If these requirements are not taken into consideration and met, then the antenna will not be efficient. The properties and natural limitations of each material candidate create a balancing act that must be carefully thought out in order to maximize the conductivity and effectiveness for a particular use.

4. Conclusion

The antipodal planar dipole featured in this report was simulated and tested with a tapered micro-strip feed line and end-launch SMA connector. Both the simulations and the data agree that the antipodal structure, tapered feed line, and reduced ground plane do not hinder the performance of the antenna, while there is some measurement error due to chamber effects. FEKO does agree best with the measured data instead of GEMS and was therefore used for simulating the antipodal structure (without a substrate) with different conductivities over the frequency band 400 to 500 MHz and as a function of trace thickness. The dipole's ohmic resistance follows an increasing trend as frequency increases and a decreasing trend as trace thickness increases, worsening for the lower conductivities. The efficiency improves when the trace thickness is doubled from 20 to 40 microns, but improvements are less drastic as the conductivity is increased, eventually becoming negligible.

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